

## HYDROLOGY AND EROSION IMPACTS OF MINING DERIVED COASTAL SAND DUNES, CHAÑARAL BAY, CHILE

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Chile has an economy strongly based on the exploitation of its natural resources. Copper mining represents the main export monetary income, employing thousands of people all along the country. The Chilean Copper Corporation (CODELCO), El Salvador branch, has been the primary mining company, but it will be ending most of its activities by 2011 unless copper prices stay at their record levels. Besides the job consequences for the local population, there are some serious environmental issues that must be solved during the shut-down.

Nearly 12 km<sup>2</sup> of contaminated sand dunes, located in the Bay of Chañaral, Chile, are the result of mining operations between 1938 and 1975 that released contaminated sediments to the bay. Even though the sediment release no longer occurs, the coastal winds transport the heavy metals attached to the sand grains over the town of Chañaral. This area is arid desert, with no more than 10 mm/year of precipitation. Between 1938 and 1990, more than 300 million Mg of highly contaminated residual sediments were deposited in the Pacific Ocean. The chemical analyses of the sediments have shown high contents of copper, iron, arsenic, zinc, cyanide, lead, aluminum, mercury, molybdenum, and other heavy metals. The toxic metals inside the sediments as well as the arid nature of this portion of the Atacama Desert have affected the establishment of almost any vegetation.

As a consequence of the exposure to the toxic mining tailings dust produced by the coastal winds, there is a high incidence of skin, lung, and eye problems in the local human population, as well as a high incidence of cancer tumors. Even though there have been some attempts at stabilizing the contaminated sand dunes, none have succeeded. The most practical solution appears to be to stabilize of

the sand dunes with multiple row tree shelterbelts next to the town of Chañaral. This paper examines the hydrologic processes which formed the sand deposits and the potential remediation program.

### STUDY AREA

#### Copper Mining

Chile is world's largest copper producer. Cuprous porphyry ore bodies that exist along the Andean Cordillera are responsible for Chile's vast mineral reserves. Some of the world's largest opencast mines are located at high altitudes and harsh cold and arid environments along the Andes Cordillera. During 2004 Chile's copper production reached 5.3 million Mg. Other metallic minerals mined and smelted in Chile include gold, silver, molybdenum, zinc, manganese and iron ore.

Copper mining has been important to Chile's economic development since the arrival of the Spanish conquerors in the 16th century. Between the 1840s and the 1880s, Chile's share of the world's copper-mining production rose to about 50%. Its share decreased to only 5% in the first half of the 20<sup>th</sup> Century, but now is expected to rise to 35–40% by 2010. Copper production in Chile reached 35% of the world market in 2000 (Velasco 2000). During the last decade, this activity has accounted for about 50% of the country's exports and foreign investment, about 5–7% of the gross national product, but less than 2% of the labor force. Copper is the main export, followed by gold, silver, molybdenum, iron, nitrates, iodine, and lithium. Some of the gold and silver and all of the molybdenum are produced as by-products of copper mining.

Most of the copper mines in Chile are located in the Andes Mountains, many in the arid to semi-arid Atacama region of the country. The three most important are: Chuquicamata at 2,680 m above sea level (22 ° 19' South Lat.; 68 ° 56' West Long.). El Salvador at 2,600 m above sea level (26 ° 15' South Lat. S.; 69 ° 34' West Long.) and El Teniente at 2,113 m above sea level (34 ° 04' South Lat.; 70 ° 21' West Long.). The environmental impact of metal

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mining activities has received world wide attention (Castilla and Nealler, 1978). In two of the large Chilean copper mines, Chuquicamata and El Teniente, pollution control is obtained by the discharge of waste waters into tailing ponds. However, throughout the history of the El Salvador mine, all untreated mining wastes have been discharged through a semi-artificial canal directly to the Pacific Ocean shore.

### **El Salvador Mine**

El Salvador is an open-pit mine, developed by block caving techniques (Camus and Dilles 2001). After milling, minerals are concentrated by basic flotation. A copper sulphide concentrate ( $\text{CuS}$ ;  $\text{CuS}_2$ ) is produced by the flotation process and transferred to the molybdenum concentration plant for the separation of molybdenum sulphide by differential flotation. The latter process requires the use of arsenic and sodium sulphide, cyanide and lime as collectors of molybdenum sulphide and depressants of copper sulphide. The copper concentrate is then sent through a pipe to the current refining plant at Potrerillos. Daily use of water in the mining and processing stages at El Salvador is  $65 \times 10^6$  L/day of water ( $2.5 \times 10^3$  L of water per ton of ore processed). Water is obtained from Andean groundwater resources. Excluding the water utilized at the molybdenum concentration plant, 40% of the water is recovered and recycled.

### **Chañaral Bay**

Chañaral Bay is situated in on the Pacific Coast of the Atacama Desert. This desert is a virtually rainless plateau along a 1,000 km strip of land on the Pacific coast of South America, west of the Andes Mountains. The rain shadow on the leeward side of the Andes keeps this 20 million-year-old desert 50 times drier than California's Death Valley. The Atacama is the second-driest desert in the world, after the McMurdo Dry Valleys of Antarctica. It occupies  $181,300 \text{ km}^2$  square kilometers ( $70,000 \text{ mi}^2$ ) in northern Chile, and consists of mostly of salt basins, sand, and lava flows. Chañaral Bay averages 20 m in depth, and doesn't deepen much until about 8 km off-shore. Chañaral is the capital of the Chañaral Department, in the Atacama

region. It is 120 km northwest of Copiapó, and had a population 10,000 in 1996. It was once an important shipping center for copper produced at the Potrerillos, Las Animas, and El Salado mines, but pro-gradation of the beach with the deposition of mine tailings ruined the harbor.

The population depended on copper industry related jobs. It declined in the 1990s with the downturn in the copper industry, but may be rebounding with surging world-wide copper prices.

### **HYDROLOGY**

The Rio Salado collects precipitation from the Andes and the Intermediate Depression of the Atacama Desert before flowing to the Pacific Ocean (Montti 1973, International Mountain Society 1984). Rainfall in the Depression is only 5 mm but it increases with altitude, reaching 33 mm at Potrerillos (elevation 2,850 m). The Rio Salado is the only permanent river in the area with an average discharge of 10 L/sec. In the vicinity of Llanta, discharge from the El Salvador Mine is added to the river.

The majority of water use in the Atacama Region (70%) is from mining. Most of this water resource is groundwater. The effects of mining withdrawals are poorly understood. The total wastewater discharge from the El Salvador Mine reaches  $39 \times 10^6$  L/d containing an average of  $25 \times 10^3$  Mg/d suspended solids. Tailing discharges from the copper and molybdenum concentration plants are routed through a 25 km long canal which discharges at the locality of Llanta into the bed of Rio Salado (Figure 1). At Llanta and Pueblo Hundido, additional recovery of copper pyrite is performed by flotation. Urban waste waters after treatment at the El Salvador sewage treatment plant are canalized 50-55 km downstream before meeting, at Pueblo Hundido, the tailing discharge stream (Rio Salado). From then on, a single stream carries both types of residues to the site of dumping in the coastal area of Chañaral. From 1938 to 1974 tailing and waste waters discharged directly into Chañaral beach (Figure. 1b). Since February 1975, a new canal collects discharges from Rio Salado, 8-10 km off Chaharal beach and carries them to a new dumping site at Caleta Palito.

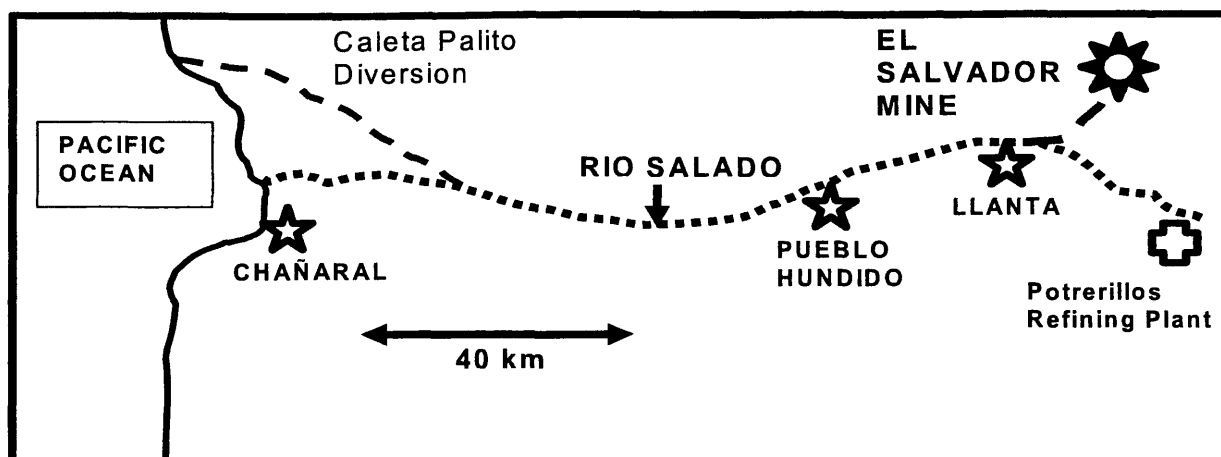


Figure 1. Chañaral Bay area of the Pacific Ocean, Rio Salado, and the El Salvador Mine, Atacama Desert, Chile.

The case of the Salado river was different. This river received tailings from the mineral-processing plant of the El Salvador mine, owned by CODELCO. The tailings completely filled in a stretch of beach in Chañaral Bay about 1 km wide and 4.5 km long. Minerals in the tailings resulted in extensive marine organism mortality (Castilla and Nealler, 1978). The El Salvador tailings dam had been filled in the original tailings dam, and the mining company, which then belonged to a US firm, allowed the tailings to spill into the Salado River. In 1975, the mining operation, which was by that time owned by CODELCO, constructed a canal to divert the river water, including tailings, to another bay, Caleta Palitos, but this action produced the same deposition effect there. Overall, the mining operation dumped  $330 \times 10^6$  Mg of tailings into the river and the canal before it was forced to change its tailings-management practices in 1989. Until 1975, more than  $150 \times 10^6$  Mg of untreated tailings were continuously discharged, directly affecting more than 20 km of coastline (Castilla, 1983; Paskoff and Petiot, 1990). From 1976 to 1989 the discharge point was moved 10 km north of Chañaral Bay to Caleta Palito ( $26^{\circ}16'S$ ,  $70^{\circ}41'W$ ), a rocky cove that received  $\approx 130 \times 10^6$  metric tons of tailings in 13 years. After the construction of an inland sedimentation dam in 1990, sediment-free wastewaters have been channeled from the dam to Caleta Palito at a flow rate of 200–250 L/s (Medina et al., 2004).

In the late 1980s, an environmental group from Chañaral took CODELCO to court. The court in Copiapó ordered the company to construct a new tailings dam. In 1989, the Supreme Court ratified the decision, and CODELCO was forced to build a tailings dam, which has now entered into operation. This was an important precedent in Chilean law: despite the outdated environmental laws covering liquid effluent, companies, even state-owned companies, could be taken to court and forced to deal with environmental problems. This case dealt with the most serious environmental impact of mining on river or sea waters in Chilean history, and it illustrates clearly that environmental policy was not a priority for CODELCO until very recently.

## SEDIMENT DEPOSITS

### Mine Tailings

Mine tailings deposited at Chañaral originate from volcanic deposits of the El Salvador-Poterillos district, located around 120 km east of Chañaral in the Atacama desert. From 1926 to 1959 the Poterillos porphyry copper deposit was mined. Hypogene alteration led to a feldspar-biotite-chlorite-quartz-ankerite-anhydrite mineralization with chalcopyrite, pyrite, bornite, molybdenite, enargite, and sphalerite as sulfide mineral assemblage (Gustafson and Hunt 1975, Camus and Dilles 2001). After 1959, the El Salvador deposit was exploited. The primary mineralization of the ore body in the 41 million-year-old El Salvador deposit is characterized by alkali feldspar-biotite-anhydrite-

chalcopyrite-bornite and chalcopyrite-pyrite mineral assemblages. Supergene enrichment formed an ore body of 1.5 km diameter and a thickness of 200 m, with replacement of chalcopyrite and bornite by mostly chalcocite and covellite (Gustafson and Hunt, 1975). Tailings deposited at Chañaral were from the secondary enrichment zone. The alkaline (pH 10.5) flotation process used for Cu and Mo extraction was controlled by lime addition and the resulting tailings were the ones ultimately deposited in Chañaral Bay.

### **Chañaral Bay**

Until 1975, mine tailings were sent into the bay at Chañaral, covering 4.5 km<sup>2</sup> (Figure 2). This resulted in a displacement of the shoreline of 1 km and the accumulation of a 10-15 m thick layer of tailings on top of the original beach sediments. The deposition point at the outlet of the Rio Salado migrated northward during the deposition period to the upper end of the "new" beach (Figure 2). The tailings originated from the Potrerillos mine from 1926 until 1939, and thereafter from the El Salvador mine until completion of the inland sedimentation dam in 1989. Between 1975 and 1989, tailings were sent to the sea at Caleta Palito, 8 km north of Chañaral, and were exposed to the marine current. The tailings deposition through the natural Rio Salado (the salty river) ceased in 1989 because of the court decision. Today, the tailings are deposited close to the "El Salvador" mine in the "Pampa Austral" tailings impoundment. Only the coarse sediment free waters of the settling pond at the Pampa Austral impoundment are mixed with highly mineralized waters in the Rio Salado riverbed close to the El Salado village. These waters are still discharged to the sea at Caleta Palito.

### **Wind Erosion**

There are about 12 km<sup>2</sup> of tailings-contaminated sand dunes, located on the recent Chañaral beach, as well as the original pre-1938 beach. Even though new sediment release no longer occurs, the coastal winds transport the heavy metals laden sand grains over the town of Chañaral.

A single, permeable row of concrete barriers was installed next to houses and along the beach with the intention of "detaining" blowing sand. However, the aerodynamic characteristics of the barrier increases

wind velocities just above the dune surface, producing even more sediment wind transport. Besides, with only one row, eddy turbulences are created due pressure differentials on both sides of the barrier. This results in sediment accumulation and burial of the barrier in newly-forming sand dunes.

Several approaches have been proposed to stabilize the mine tailings sand dunes. The sediments could be easily stabilized if the wind was gradually forced to rise over permeable barriers. The strong coastal winds blowing a few meters above the sand dune surfaces would be less likely to transport sand grains. Tree shelterbelts have been proposed as a mitigation measure for the beach wind erosion. However, soil would need to be imported due to the contaminated nature of the Chañaral sands, and water would need to be applied via an irrigation system due to the arid nature of the climate (<10 mm rainfall per year).

### **HEALTH IMPACTS**

Mine tailings can cause human disease via exposure routes of water, dust, and crops. Diseases can range from direct toxicity to physical effects, silicosis, hypothyroidism, etc. Chemical analyses of the Chañaral Bay sediments have shown the existence of high contents of copper, iron, arsenic, zinc, cyanide, lead, aluminum, mercury, molybdenum, and other heavy metals. As a consequence of the exposure to the toxic dust produced by the coastal winds, there is a high incidence of skin, lung, and eye problems, as well as a variety of cancer tumors among Chañaral's population (Leon 2001). Concerns about perchlorate in Chañaral's drinking water affecting thyroid function of children were never validated (Crump et al. 2000).

### **SUMMARY**

Nearly 12 km<sup>2</sup> of contaminated sand dunes, located in the Bay of Chañaral, Chile, are the result of mining operations at the El Salvador Mine between 1938 and 1975 that released contaminated sediments to the bay via the Rio Salado. About  $150 \times 10^6$  Mg of untreated tailings were deposited in Chañaral Bay before a diversion was put in place

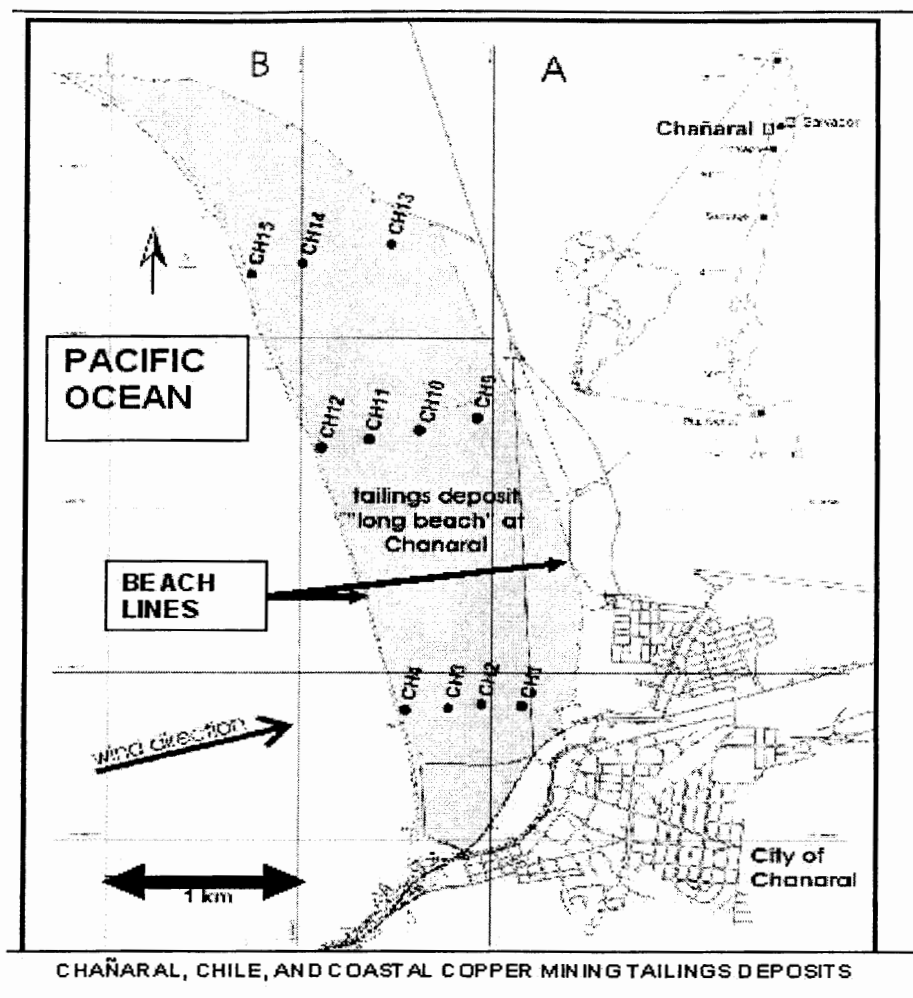


Figure 2. Chañaral Bay, Chile (A), showing beach deposits and progradation (B) from 1938 to 1989 (Adapted from Wisskirchen and Dold 2006)

Chañaral Bay before a diversion was put in place to Caleta Palito. Another  $180 \times 10^6$  Mg of tailings was deposited in the Pacific Ocean before a large tailings dam was constructed at the mine. The total wastewater discharge from the El Salvador Mine reaches  $39 \times 10^6$  L/d, resulting in a flow in the Rio Salado of 200–250 L/s. Even though the sediment release no longer occurs because of the diversion north of Chañaral Bay, the coastal winds transport the heavy metals attached to sand grains over the town of Chañaral. The source of these sands is 4.5 km<sup>2</sup> of beach formed since 1938. Biological stabilization of the sand dunes is complicated by the arid climate and toxicity of the sands.

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